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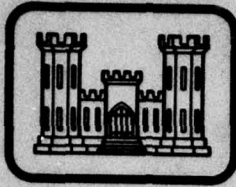
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REPAIR OF CONCRETE SURFACES SUBJECTED TO ABRASION EROSION DAMAGE

by

James E. McDonald, Tony C. Liu

Structures Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A survey of Corps Divisions and District offices identified 54 structures that have experienced concrete damage due to erosion. Depths of erosion ranged from a few inches to approximately 10 ft. In general, this erosion damage resulted from the abrasive effects of waterborne rocks and other debris being circulated over the concrete surface during construction and operation of the structure.		

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20. ABSTRACT (Continued)

CONT → A variety of materials including armored concrete, conventional concrete, epoxy resins, fiber-reinforced concrete, and polymer-impregnated concrete have been used in the repairs reported herein with varying degrees of success, the degree of success generally being inversely proportional to the degree of exposure to those conditions conducive to erosion damage. These materials have been used with various construction procedures including dewatering and under-water repairs.

It appears that given appropriate flow conditions in the presence of debris, all of the materials described are susceptible to some degree of erosion. No one material has demonstrated a consistently superior performance advantage over alternate materials. While improvements in materials should reduce the rate of concrete damage due to erosion, this alone will not solve the problem. Until the adverse hydraulic conditions which caused the original damage are minimized or eliminated, it will be extremely difficult for any of the materials currently being used in repair to perform in the desired manner.

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PREFACE

This paper was prepared for the Symposium on Deterioration of Concrete held 21 March 1979 in Milwaukee, Wisconsin, in conjunction with the ACI Annual Convention. The information discussed herein was compiled as a part of the Civil Works Research Program, Work Unit 31553, Maintenance and Preservation of Civil Works Structures, sponsored by the Office, Chief of Engineers. This study is being conducted by the Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

Funds for the publication of this paper were provided from those made available for operation of the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 40. The report was prepared by Messrs. J. E. McDonald, Chief, and T. C. Liu, Research Structural Engineer, Structures Branch, SL, under the general supervision of Messrs. Bryant Mather, Acting Chief, SL, and J. M. Scanlon, Chief, Engineering Mechanics Division, SL.

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REPAIR OF CONCRETE SURFACES SUBJECTED TO ABRASION EROSION DAMAGE

INTRODUCTION

The Structures Laboratory, USAE Waterways Experiment Station (WES), is currently conducting a comprehensive research program to identify and evaluate various materials for repairing and improving the resistance of concrete subjected to abrasion erosion. One phase of this investigation is concerned with spillway aprons and stilling basins. A typical stilling basin design includes a downstream end sill, 3- to 20-ft (1- to 6-m) high, intended to create a permanent pool to aid in energy dissipation of the high-velocity flows. Unfortunately, these pools also serve, in many cases, to trap large boulders, riprap, reinforcing steel, and similar debris. While quality concrete is capable of resisting high water velocities for many years with little or no damage, it cannot withstand the abrasion due to the grinding action of the entrapped debris. Individual pieces of debris will ultimately erode local holes to depths of several feet, in some areas completely through the concrete floor slab.

CONCRETE DAMAGE

A survey of Corps Division and District offices identified 54 structures which have experienced concrete damage due to abrasion erosion. These structures had extensive areas of erosion to depths of 6 in. (152 mm), and in many instances localized erosion had penetrated to depths of 2 to 6 ft (0.6 to 1.8 m). At the deepest point (approximately 10 ft (3 m)) erosion in the Dworshak Dam stilling basin had progressed completely through the concrete and into the granite bedrock. In this case, nearly 2000 cu yd (1529 cu m) of concrete and bedrock were removed from the stilling basin by erosion.

DESCRIPTION OF REPAIRS

Of the 54 structures identified with erosion damage, 33 have been repaired with over 70 percent of the repairs being performed since 1970.

A variety of repair materials and techniques including armored concrete, conventional concrete, epoxy resins, fiber-reinforced concrete, polymer-impregnated concrete, and tremie concrete have been utilized with varying degrees of success. This paper describes design and construction details associated with representative repairs of each type. Also, the results of available follow-up inspections and evaluations to determine performance are presented and the relative merits of the various systems are discussed. Additional details on the damage and repair of these and other structures are presented in Reference 1.

Old River Low Sill Structure

Of the several repair concepts proposed for this structure, it was determined that prefabricated modules of steel plate anchored to the end sill and to the floor slab directly behind the downstream row of baffle blocks would be used to repair the basin. Although this plan appeared to present a significant change (hydraulically) to the stilling basin, model tests² indicated that it would not create adverse hydraulic conditions in the stilling basin and exit channel. Thirty modules 24-ft (7.3-m) long and varying in width from 3 to 22 ft (1 to 6.7 m) were fabricated from 1/2-in. (13-mm) thick steel plate. Vertical diaphragm plates were welded to the horizontal plate, both to stiffen the plate and to provide a formed void in which to retain the grout. After individual modules were positioned and anchored, a portland cement grout containing 1-in. (25-mm) steel fibers was pumped into the modules beneath the water.

An underwater inspection 8 months after the repairs showed 7 of the 30 modules had lost portions of their steel plate ranging from 20 to 100 percent of the surface area. A number of anchor bolts were found broken either flush with the plate, flush with the grout, or pulled completely out. In those areas where steel plating was lost, the exposed grout surfaces showed no evidence of significant erosion.

A second inspection of the repairs in November 1978, approximately 2 yr after repair, revealed that additional steel plate had been ripped from four of the modules previously damaged. Also, that an additional 9 modules had sustained damage. Minor erosion had occurred in the

stilling basin slab upstream from the modules. No deterioration of the fiber-reinforced grout was reported. The stilling basin was reported to be free from rock and other debris. Apparently, any rock or debris discharged through the structure is flushed from the stilling basin over the fillet formed by the modules at the end sill.

Bull Shoals Dam

The original elliptical-step-type stilling basin was constructed in 1948-49. The aggregates used in the stilling basin concrete were manufactured from a material consisting of approximately 80 percent sandy dolomitic limestone and 20 percent sandstone. The compressive strength at 28-days age averaged approximately 3600 psi (25 MPa).

Inspection of the unwatered basin in 1952 revealed deposits of sand, gravel, timber, and miscellaneous scrap steel. Most of the pieces of rock and steel had been rounded by abrasion. The location of the largest deposit coincided with the area of maximum erosion. Areas of eroded concrete and exposed reinforcing steel were present on or immediately downstream from the first elliptical step below 12 of the 16 conduit outlets and on or immediately downstream from the second step below 6 of the conduit outlets. The initial damage was attributed to cavitation with subsequent abrasion by the eroded material.

As a temporary repair of the basin while it was dewatered, it was decided that the damaged steps should be cut back and replaced with smooth upward sloping slabs, the slabs replacing the two upstream steps at 14 conduit outlets and replacing all four steps at one outlet. The undamaged steps at the remaining conduit were retained for testing purposes.

Concrete in the stepped areas was broken with paving breakers and excavated by hand. Anchors were grouted into holes drilled on 4-ft (1.2-m) centers each way and reinforcing mats were welded to the anchors. In an attempt to obtain increased abrasion resistance, it was decided to use a natural siliceous sand as fine aggregate in the repair concrete. The sand was composed of 83 percent dense particles of quartz, 10 percent feldspar, and 7 percent of other miscellaneous minerals. The coarse aggregate was the same as that used in the original construction. All

concrete surfaces were given a hard troweled finish. Average compressive strengths at 7 and 28 days were 3630 and 5820 psi (25 and 40 MPa), respectively.

Although the original model studies of the stilling basin had not revealed the existence of any large negative pressures which might have caused cavitation, it was decided to install 16 pressure cells in the stilling basin in conjunction with the repair work. Prototype tests, conducted in January 1953, disclosed that pressure fluctuations downstream from the top of the first step, as originally constructed, were in the cavitation range for operations at half-gate opening; at full-gate opening, pressure cells at this position were pulled out of the concrete and no reading was possible. Cells located just downstream from the end of the temporary ramp covering the first two steps recorded pressures that were consistently negative. Pressure fluctuations into the cavitation range also were noted near the beginning of the sloping ramp where positive pressures were expected.

Model tests³ were conducted during 1953-54 to determine a satisfactory method of making permanent repairs to the stilling basin. These tests indicated the existing 4-ft (1.2-m) high end sill was inadequate for dissipating energy from conduit flow when the smooth floor ramp was installed. A higher end sill produced an adequate hydraulic jump under spillway discharge, but was somewhat less effective than the low end sill in preventing erosion in the exit channel. Baffles provided improved stilling action for spillway flows, but were of negligible value for conduit discharges.

Based on the results of these tests a contract was awarded in June 1954 for construction of one row of baffles, 8 ft (2.4 m) in height. Also, the end sill was increased in height to 12 ft (3.7 m) and a 19.5-ft (5.9-m) long horizontal apron terminated by another 2-ft (0.6-m) high sill was provided downstream for protection of the exit area during periods of low flow.

The stilling basin was inspected by a scuba diver in 1968. The concrete in the repaired section of the stilling basin floor exhibited degradation estimated to range from 3/4- to 3-in. (19- to 76-mm) deep.

The deeper scars occurred along monolith joints. The degradation of the original concrete, while similar in depth, occurred in a more widespread pattern across the floor. A large collection of well-rounded aggregates was piled up on the floor of one monolith. In general, the condition of the stilling basin was considered satisfactory.

Pomona Dam

The original concrete in the transition and stilling basin slabs was proportioned with Kansas River natural sand and Stoner limestone (1-1/2-in. (38-mm) maximum size aggregate (MSA)). Compressive strengths at 28 days were in excess of 5000 psi (34 MPa). After approximately 6 years operation, the basin was dewatered for inspection in February 1968. Erosion, caused by the abrasive action of rocks and other debris, had occurred at the downstream end of the transition slab and on the upstream one-third of the basin slab. A supplemental inspection in October 1970 revealed significant additional concrete erosion with extensive exposure of reinforcing steel.

Based on a model study, it was recommended that the most practical solution was to provide a 2-ft (0.6-m) thick overlay slab to the upstream three-fourths of the basin slab. This solution provided a wearing surface for the area of greatest erosion and provided a depression at the downstream end of the basin for trapping debris. However, flow separation and eddy action were not eliminated by this modification. It was also recommended that the basin operation be revised.

The basin was dewatered for inspection and repair in October 1972. Additional erosion was observed; however, the rate of erosion appeared to have decreased. This reduction was attributed to a decrease in the number of days with discharges above 500 cfs (1416 cu m/s). The repair included (1) a minimum 1/2-in. (13-mm) thick epoxy mortar applied to approximately one-half of the transition slab, (2) an epoxy mortar applied to the upstream face of the right three upstream baffles, (3) a 2-ft (0.6-m) thick concrete overlay slab placed on the upstream 70 percent of the basin slab, and (4) a sloped concrete end sill.

The surfaces to receive the epoxy mortar were cleaned by sandblasting to expose approximately 50 percent aggregate. The cleaned surface was

primed with epoxy resin binder just prior to placement of the epoxy mortar. Specifications required the epoxy coatings to be kept dry and above 60F (16C) for a period of one week. However, during a period of rainy weather, backwater flooded the epoxy overlay. At the time of flooding approximately 80 percent of the epoxy mortar was placed and had 2 days of curing under specified conditions. Problems with moisture seepage through construction joints required patching of areas along the joints with a quick setting, moisture compatible epoxy.

The reinforced concrete overlay was recessed into the original transition slab and anchored to the original basin slab. The coarse aggregate used in the repair concrete was Iron Mountain trap rock, an abrasion resistant aggregate. The average compressive strength of the repair concrete was 6790 psi (47 MPa) at 28-days age.

When the basin was dewatered in April 1977, the depression at the downstream end of the overlay slab appeared to have functioned as desired. Most of the debris, approximately 1 cu yd (0.8 cu m) of rocks, was found in the trap adjacent to the overlay slab. The concrete overlay had suffered only minor damage with general erosion of about 1/8 in. (3 mm) with maximum depths of 1/2 in. (13 mm). The location of the erosion coincided with that occurring prior to the repair. Apparently, debris is still being circulated at some discharge rate.

The epoxy mortar overlay had not suffered any visible erosion damage, however, cracks were observed in several areas. In one of these areas the epoxy mortar coating was not bonded to the concrete. Upon removal of the mortar in this area (approximately 25 sq ft (2.3 sq m)) it was observed that the majority of the failure plane occurred in the concrete at depths up to 3/4 in. (19 mm). Following removal, the area was cleaned and backfilled with a low modulus, moisture-insensitive epoxy mixed with approximately 3-1/4 parts sand to 1 part epoxy. In all other areas, even those with cracks, the epoxy mortar appeared to be well bonded.

Based on a comparison of discharge rates and slab erosion, before and after the repair, it was concluded that the repair had definitely reduced the rate of erosion. The debris trap and the abrasion resistant concrete were considered significant factors in this reduction.

Enid Dam

After gate closure the stilling basin was dewatered by pumping. Silt and debris were removed by hosing with water and shovels. Loose concrete and previous temporary repairs were removed with jackhammers. All surfaces to be repaired were then sandblasted after which they were thoroughly cleaned and dried prior to application of the epoxy bonding course.

The epoxy resin bonding material was mixed and applied to the receiving surfaces immediately prior to placement of the filler concrete. Stiff stable brooms were used to insure complete coverage of the receiving surface with bonding material. Filler concrete proportioned with 3/4-in. (19-mm) MSA for a 28-day compressive strength of 4000 psi (28 MPa) was placed while the bonding course was still wet. Maximum depth of the repair concrete was about 12 in. (305 mm).

After finishing was completed, the concrete was cured under polyethylene for 3 days. At the end of the curing period the polyethylene was removed and the concrete lightly sandblasted to remove surface laitance and produce a roughened surface. A light prime coat of neat epoxy was then applied to the thoroughly cleaned and dried concrete followed by a 1/4-in. (6-mm) epoxy mortar sealer and wearing course. The mortar, consisting of one part epoxy to three parts silica sand, was mixed in a mortar mixer. The mortar was finished to desired grade with steel trowels.

Surface preparation on the baffles was similar to that previously described for the basin floor slabs. Immediately after application of the epoxy bonding material, epoxy mortar was hand trowelled onto uneroded areas of the baffles to a minimum thickness of 1/4 in. (6 mm). On eroded areas, the thickness of coating was that necessary to restore the baffles to their original dimensions.

An inspection of the repairs after 2 years service indicated excellent bond between the epoxy mortar and fill concrete. With the exception of two relatively small areas, one on each side of the longitudinal splitter wall, the epoxy mortar exhibited good resistance to abrasion erosion. In both cases, erosion occurred in a generally circular pattern

around the upstream baffle nearest the splitter wall. This generally coincided with the areas of maximum erosion prior to repair. The maximum depth of erosion was approximately 1/2 in. (13 mm). The condition of the mortar at construction joints was of some concern during the repair due to moisture seepage; however, the mortar in these areas appeared similar to that elsewhere. The baffles were in excellent condition with no evidence of erosion.

Chief Joseph Dam

Extensive areas of eroded concrete were discovered in the stilling basin during an underwater inspection in March 1957, two years after the project became operative. By 1966 erosion had progressed to maximum depths of approximately 6 ft (1.8 m), with the most severe erosion located in areas between the row of baffles and the end sill. Therefore, it was decided to repair portions of eight of the basin slabs using pumped concrete and preplaced aggregate concrete.

Prior to the concreting operations, debris was removed from the repair areas, exposed reinforcement was cleaned, and an estimated 6200 sq ft (576 sq m) of concrete surface area was cleaned. Holes for anchors were drilled, filled with grout, anchors embedded, and the horizontal reinforcement positioned.

In the preplaced aggregate concrete operations, concrete buckets containing the coarse aggregate were guided into position and dumped by a diver. Screeds placed on preset edge forms were then used by the divers for leveling the aggregate to the proper grade before placing the top form panels. Grout pipes were driven the full depth of the coarse aggregate. The grout mixer and pumps were set up on a training wall and grout was first pumped through grout pipes in the deepest area of the placement until a return appeared through the vent pipes surrounding that area. These were plugged with corks when good sanded grout appeared. When grout appeared in the next row of vent pipes the grout hose was moved to an adjacent pipe and the grout hole plugged. This procedure was continued until the entire form had been pumped. Approximately 80 cu yd (61 cu m) of preplaced aggregate concrete were required in the repair.

Concrete was batched at a local supplier and delivered to the site in transit mixers. At the site the material was placed in a collection hopper on a training wall and delivered from this point through a 10-in. (254-mm) pipe into concrete buckets on a power barge for ferrying to the pump sites. From this point the concrete was pumped with delivery through a 3-in. (76-mm) hose. The last 2 ft (0.6 m) of this hose was fitted with a metal tube to allow ready insertion of the conduit into the concrete when leveling off the surface. A clamp was located just above the metal tube to provide the required valve action and allow the placement to be controlled by the diver. The concrete mixture produced a workable material that was easily placed and produced a smooth even surface which flowed well. Surface slopes estimated at 12:1 were achieved. The measured surface area of tremie concrete was 439 sq yd (367 sq m).

The repairs were accomplished in September through December 1966. During the high water season in 1967 the repairs were subjected to peak discharges of 432,000 cfs (1,223,000 cu m/s), a flow with a frequency of recurrence of about once in 6 years. A December 1967 inspection of the repairs showed the preplaced aggregate concrete surfaces to be in excellent condition. Inspection of several surface marks previously noted during acceptance inspections showed no discernible change. The inspection also showed the pumped concrete surfaces to be in good condition with only minor surface damage noted. The worst damage occurred to the first placement of pumped concrete where the design mix proved to be too stiff and had a tendency to form a roll at the outside edges. Small depressions in pumped concrete surfaces noted during the acceptance inspection were unchanged.

A detailed inspection of the stilling basin conducted in 1974 indicated there had been no extensive erosion of the stilling basin since the repairs were made. This inspection indicated there were some areas in the basin where aggregate rebar were exposed, with the average depth in these particular areas ranging from 0.6 to 1.7 ft (0.2 to 0.5 m). However, this erosion was present prior to 1964 and the rate of erosion has been minimal from 1964 to 1974.

Webbers Falls Dam

Although the erosion in the stilling basin at Webbers Falls was severe enough in places to warrant attention, it was not considered a serious threat to the integrity of the structure. However, it was decided to fill the deepest holes with concrete placed by tremie, and 21 cu yd (16 cu m) were placed. This concrete was subjected to normal operating conditions for several months and then examined by a diving team. The concrete was still intact and cores from the area indicated a good bond with the old concrete. Placements were then made in other eroded areas.

Conventional concrete placed with a 10-in. (254-mm) diameter tremie pipe was used to fill the eroded areas. The concrete was designed for a cement content of 752 lb per cu yd (446 kg/cu m) and a water content as required to obtain a 5- to 8-in. (127- to 203-mm) slump. During the placing operation, the mixing water was heated to about 150F (66C) to offset the effect of the cold river water.

A work platform was constructed over the area to be repaired by lashing several barges together. Prior to placing concrete the damaged area was air cleaned of silt and debris. The concrete was transported to the tremie area by loading the transit mixers on barges. A placement was made by transferring the concrete from the truck into a concrete bucket. The bucket was then positioned by crane over a hopper attached to the tremie pipe. A "rabbit" comprised of a greased polyethylene bag filled with burlap bags was placed in the top of the tremie prior to placing concrete in the hopper. The bottom of the tremie pipe was positioned by divers and rested on the surface of the existing concrete. When the concrete forced the rabbit to the bottom of the pipe, the pipe was raised approximately 1 ft (0.3 m) to eject the rabbit and permit the flow of concrete. This process was repeated each time it was necessary to move the tremie pipe.

A total of 43 cu yd (33 cu m) of concrete was placed during two different periods. The depth of the water in the stilling basin during the repair was about 40 ft (12 m) and the water velocity was 3 to 4 fpm (0.9

to 1.2 m/m) due to releases through the adjacent power plant. No releases were made through the spillway for 7 days following the concrete placement.

Cores taken through the tremie concrete had an average compressive strength of 5250 psi (36 MPa) at about 60 days age and exhibited good bond between the new and existing concrete. A diving team made a cursory inspection of the repaired areas about 1 year after repair and found them to be in good condition even after experiencing high flows.

Kinzua Dam

Because of the proximity of a pumped storage power plant on the left abutment and problems from spray, especially during the winter months, the right side sluices at Kinzua Dam were used most of the time. This caused a circulatory current which carried debris into the stilling basin, the end sill being below streambed level. As a result, erosion of the concrete to depths of 42 in. (1 m) was reported less than 4 years after the basin was placed into normal operation.

The repair work was accomplished in two stages using cellular cofferdams which enclosed about 60 percent of the stilling basin for each stage permitting stream flow in the unobstructed part of the stilling basin. In preparation for the repair, the floor of the stilling basin was cleaned by wet sandblasting. Loose, weak, or deteriorated concrete was removed by chipping. All loose materials and impurities were then removed by washing or wet sandblasting and No. 8 dowels were installed on approximately 3-ft (0.9-m) centers. The deeper holes were partly filled with dense concrete having a 28-day compressive strength of 3000 psi (21 MPa). A concrete mixture containing 1-in. (25-mm) steel fibers, proportioned for 1100 and 6000 psi (6 and 41 MPa) flexural and compressive strengths, respectively, was used for the overlay.

A high modulus epoxy bonding compound was placed on the stilling basin floor immediately prior to placement of the fibrous concrete overlay. The overlay was placed in slab sections conforming to the original slabs. Relief drains were extended through the overlay. Approximately 1400 cu yd (1070 cu m) of fiber concrete were required for the overlay which was placed to an elevation 1 ft (0.3 m) higher than the original

stilling basin floor from the toe of the dam to a point just short of the downstream end of the baffle piers.

The baffles were prepared for repair in the same manner as the stilling basin slab. Dowels were installed and an epoxy bonding compound applied. The front of the baffles was resurfaced with fibrous concrete and reinforced with No. 8 steel bars. In addition, corner pieces of corrosion resistant steel plate, 5/8-in. (16-mm) thick, were installed at the upstream corners of the baffle piers. Both sides, the top, and the back of damaged baffles were coated with an epoxy mortar. This same mortar, a 1 to 1 ratio of epoxy and silica sand, was used to coat the damaged spillway surface to a 1/2-in. (13-mm) average thickness.

The initial diver inspection of the repair in November 1974, 1 year after completion of Stage I repairs, indicated minor concrete deterioration on some of the baffles and in the surrounding floor area. Two large areas of epoxy repairs at the base of the spillway were missing. An estimated 45 cu yd (34 cu m) of debris was removed from the basin.

In April 1975, additional concrete erosion on five baffles and in the floor area between and downstream of the baffles was noted. Trenches around some baffles had approximate maximum depths of 4 to 12 in. (102 to 305 mm). The fiber concrete overlay upstream of the baffles contained several areas of erosion ranging in depth from 5 to 17 in. (127 to 432 mm). Additional areas of epoxy repairs at the bottom of the spillway were missing. Again, approximately 45 cu yd (34 cu m) of debris were removed from the stilling basin.

Continued erosion of the fiber concrete was noted in subsequent inspections until a policy of symmetrical sluice operation was adopted. This appears to have essentially eliminated the problem of bringing debris into the basin from downstream and, as a result, additional concrete erosion since September 1975 appears minimal.

Dworshak Dam

Following dewatering and a thorough cleanup, eroded areas of the stilling basin floor were filled to within 15 in. (381 mm) of final floor elevation with 730 cu yd (558 cu m) of structural grade unreinforced fill concrete. This concrete was pumped from the top of the

training wall down to a horizontal pipe which extended from 50- to 250-ft (15- to 76-m) out to the placement area.

Prior to placing the fiber concrete topping, No. 8 anchor bars were placed in rotary percussion holes on 5-ft (1.5-m) centers and grouted with a nonshrink cement grout. A horizontal mat of No. 6 reinforcing bars on 15-in. (381-mm) centers was hooked to the anchor bars. Flexural and compressive strengths of the fiber concrete mixture were approximately 860 and 8000 psi (6 and 55 MPa), respectively, at 28-days age.

Existing construction joints in the stilling basin were continued through the topping of fiber concrete. The fiber concrete was placed using a crane and two concrete buckets. Internal vibrators were used to consolidate the concrete and a vibrating screed was used to strike off the surface. Following the fiber concrete placement, the right half of the stilling basin was impregnated with methyl methacrylate (MMA) monomer.

Each area to be polymerized was enclosed and dewatered with a wet vacuum to reduce the time required to dry the concrete. Sand was then applied by hand within the enclosed area to a depth of approximately 3/8 in. (10 mm). The sand acted as a wick to ensure uniform distribution of the monomer during the saturation phase. Drying of the concrete within the enclosure was accomplished using infrared heat lamps. Roof sections of the enclosure were then removed and monomer was applied over the sandbed by gravity through a spray bar that extended the width of the enclosure. The insulated steel cover was then replaced and the entire enclosure covered with polyethylene sheeting to prevent evaporation during the soak period. At the conclusion of the soak period the monomer was polymerized by heating the saturated concrete with steam heat for a period of 1 hr at approximately 200F (93C).

In areas where erosion of the original concrete was less than the 15-in. (381-mm) minimum depth specified for the fiber concrete topping, the design called for removal of the existing concrete to this depth. However, one section of the stilling basin floor and the lower portion of the spillway exhibited only minimal erosion to a maximum depth of about 4 in. (102 mm). Therefore, it was decided to repair both sections,

totaling approximately 5100 sq ft (474 sq m), with an epoxy mortar topping. This work was completed using several types of epoxy mortar, the primary one, a stress-relieving material which was slow curing and had a low exotherm. There were several problems that occurred with the epoxy during application which were primarily the result of workmanship, weather conditions, and failure to enclose the work area. Under the cool conditions that existed, the epoxy mortar probably did not receive full cure before the stilling basin was put back into service.

It was originally planned to repair the walls of the stilling basin using procedures similar to that for the floor. However, the walls were in reasonably good condition; consequently, they were rapidly and economically repaired with a high-strength shotcrete mortar.

During the 7 months between completion of repairs and the initial diver inspection, the basin was subjected to a total of 53 days usage (9 days from the spillway gates and 44 days from the regulating outlets). The spillway and outlet gates were operated symmetrically (or very close to it) for all spills. Total flows varied between 2,100 and 20,000 cfs (5,950 and 56,600 cu m/s), with the majority being on the order of 3,000 to 10,000 cfs (8,500 and 28,300 cu m/s).

The underwater inspection by diver indicated no major erosion or damage. The stilling basin walls had a small amount of surface erosion (less than 1 in. (25 mm)). There were several areas at the junction between the floor and wall with erosion up to 3-in. (76-mm) deep. An estimated 25 percent of the surface area of the epoxy mortar had experienced some degree of failure ranging up to 4-in. (102-mm) depths. The fibrous concrete (both polymerized and non-polymerized) was generally in good condition. In general, the polymer-impregnated side was probably a little better than the non-polymerized side. There were several areas of erosion in the center of the basin several feet in diameter and dished out up to an inch (25 mm) deep. Joints and open cracks in the entire basin (including fibrous concrete) were the most susceptible to damage. Typical joints and open cracks in the fiber concrete had eroded up to about 1-in. (25-mm) deep at the joint and tapered out to the original floor surface within a foot (0.3 m) of the joint. Because of moisture

in the joints and cracks during the repair, concrete at joints and cracks was not impregnated. There were isolated accumulations of gravel, rebar, and debris at a number of locations throughout the basin.

Four months later, after some additional usage of the stilling basin, a diver was employed to clean the debris from the basin and provide more information on the condition of the floor. Significant comments resulting from this inspection were that there were large areas of the concrete surface near the center of the basin with grooves 2- to 3-in. (51- to 76-mm) deep. These grooves, in both the polymerized and non-polymerized fiber concrete, are oriented in the direction of flow.

Upper St. Anthony Falls Lock

The lock was dewatered in December 1975 to repair a damaged miter gate. During this period an examination of the filling and emptying laterals and discharge laterals revealed considerable abrasion erosion of the concrete to maximum depths of 23 in. (686 mm). This erosion was caused by rocks up to 18-in. (457-mm) diameter which had made their way into the laterals. Subsequent filling and emptying of the lock during normal operation agitated these rocks causing them to erode the concrete.

Damaged concrete was removed from the discharge laterals with the use of hand power tools to a minimum depth of 3 in. (76 mm) and all damaged reinforcing steel was repaired or replaced. A neat cement slurry was applied to the floors of the laterals and epoxy was applied to the walls before the placement of concrete. Approximately 40 cu yd (31 cu m) steel fiber-reinforced concrete was used in the repair of the discharge laterals. Average test results for this concrete were 965 and 6760 psi (7 and 47 MPa) for flexural and compressive strengths, respectively, at 28-days age. In addition, 1/2-in. (13-mm) thick steel plate was anchored on the floor and walls in the center discharge lateral.

It was decided to make the floor of one of the filling and emptying laterals a test section for different repair materials, as described in the following.

a. Epoxy mortar. A low-modulus epoxy mortar, 1/2- to 1-in. (13- to 25-mm) thickness, was used to overlay a section of conventional concrete. The mortar consisted of 1 part epoxy to 3 parts silica sand.

Conditions during the repair were described as fair to poor with too much standing water to do a good job.

b. Conventional concrete. Conventional concrete bonded to the old concrete with an epoxy-bonding agent was used in the repair of two sections. No record of mixture proportions or strength characteristics of this concrete could be located. The concrete appeared to have 3/8-in. (10-mm) MSA, and there was speculation that the fiber concrete mixture, minus the fibers, was used.

c. Fiber concrete. In the test section 1/2-in. (13-mm) steel fibers were substituted for the 1-in. (25-mm) fibers used in the discharge laterals. Average test results were 730 and 5770 psi (5 and 40 MPa) for flexural and compressive strengths, respectively, at 28-days age.

d. Epoxy concrete. Two 12- by 24- by 6-in. (305- by 610- by 152-mm) sections were repaired with low-modulus epoxy concrete. Mixture proportions (yield approximately 1/2 cu ft (1.4 cu m)) were 1 gal (3.8 cu m) of epoxy, 25 lb (11.3 kg) of grit, and 20 lb (9.1 kg) of silica sand. It was the opinion of the epoxy representative present during the repair that the chances of getting good results were slim due to free water and sand in the holes prior to placement.

e. Steel plate. One section of an abrasion-resistant steel plate (1/2-in. (13-mm) thickness) was anchored to conventional concrete.

Prior to filling the lock chamber, rocks that caused the erosion damage were returned to their original positions in the lateral to provide a positive test of the repairs. Approximately 2 years after the repairs dewatering of the lock allowed an examination of the repairs with results as follows:

a. Epoxy mortar. In spite of the pessimism during placement, the epoxy mortar repair appeared to have performed fairly well. With the exception of some minor erosion along the edges of the repair and a few small localized areas within the repair where the overlay appeared to be very thin, the epoxy mortar was in good condition.

b. Conventional concrete. There was general erosion of the entire concrete section exposed to abrasion by the rocks. At maximum depths (approximately 6 in. (152 mm)) erosion extended completely through the

repair and into the old concrete. The section of conventional concrete adjoining the river wall was not subjected to the abrasive effects of waterborne rocks and appeared to be in essentially original condition.

c. Fiber concrete. The fiber concrete in the discharge laterals was not subjected to the abrasive effects of waterborne rocks in the laterals and erosion in these areas was negligible. In comparison, fiber concrete in the test section which was exposed to abrasion by rocks exhibited considerable erosion. The pattern and extent of erosion was almost identical to the adjacent conventional concrete repair. There was speculation that the relatively slick finish on the epoxy mortar and steel plate on the boundaries of the eroded areas of fiber and conventional concrete may have contributed to a concentration of rocks in the eroded areas. In fact, the major areas of erosion in the conventional and fiber concretes were connected, indicating a transition of rock between the two areas.

d. Epoxy concrete. As was the case with the epoxy mortar, pessimism during placement appears to have been unfounded. The section of epoxy concrete repair subjected to abrasion was essentially intact with only slight erosion of the two corners which extended into the transition path between the fiber and conventional concrete erosion. The erosion resistance of the epoxy concrete is particularly significant considering that erosion in portions of the adjacent conventional and fiber concrete extended to their full depth and into the original concrete. However, the repair area is small and being directly opposite the filling and emptying port, abrasion by boulders within the lateral may not have been as severe as areas between the ports. The second area of epoxy concrete was not subjected to the abrasive effects of rocks and appears to be in essentially original condition.

e. Steel plate. The plate was on the boundary between the rock and no rock sections and as might be expected exhibited little sign of wear although the adjacent fiber concrete was eroded and the nut on one of the anchor bolts was missing.

DISCUSSION AND CONCLUSIONS

The repair materials and techniques discussed herein have been in service for various lengths of time and have been exposed to different operational conditions as well as different levels and durations of flow. This makes any comparison of the relative merits of the various systems difficult at best; however, a number of general conclusions are offered in the following.

Materials

The resistance of steel plate to abrasion erosion is well established, however, it must be sufficiently anchored to the underlying concrete to resist the uplift forces and vibrations created by flowing water. Welding of anchor systems as nearly flush with the plate surface as possible appears more desirable than raised bolted connections. In any case, the ability of the anchor system, including any embedment material, to perform under the conditions of exposure, including fatigue, should be evaluated in detail during design of the repair.

No erosion of the fiber grout at Old River has been reported. However, the location of this material on a 1 in 7 slope at the end sill should significantly reduce the effects of abrasion forces. Both the epoxy mortar and the fiber concrete failed under the severe abrasion condition existing at Kinzua prior to adoption of a symmetrical sluice operation policy. Under comparable conditions at Upper St. Anthony Falls both conventional and fiber concrete failed, whereas, epoxy mortar and epoxy concrete performed satisfactorily in spite of adverse placing conditions. After 1 year exposure to limited discharges at Dworshak, fiber concrete (both polymerized and non-polymerized) was generally in good condition with maximum erosion 2- to 3-in. (51- to 76-mm) deep.

An estimated 25 percent of the epoxy mortar at Dworshak had failed probably due to workmanship, weather conditions, and lack of sufficient curing during construction. After 2 years exposure at Enid, the epoxy mortar had excellent bond to the fill concrete and generally good abrasion resistance. The rate of maximum erosion was approximately one-half that occurring prior to repair. No erosion damage to the epoxy mortar

was visible at Pomona, however, there were several areas of cracking and loss of bond attributed to improper curing and thermal incompatibility with existing concrete.

Conventional concrete exhibited erosion of $3/4$ to 3 in. (0.9 to 76 mm) after 13 years exposure at Bull Shoals. Similar concrete containing abrasion resistant aggregate had general erosion of $1/8$ to $1/2$ in. (3 to 13 mm) after 5 years exposure at Pomona. Placement of concrete underwater did not have any adverse effect on its abrasion resistance as evidenced by the results at Chief Joseph and Webbers Falls.

Regardless of the material, construction joints are generally the areas most susceptible to abrasion erosion. Therefore, they should be given appropriate attention in the design and construction of any repair.

Indications are that given appropriate discharge conditions in the presence of debris, all of the materials used are susceptible to some degree of abrasion erosion.

Revised Configuration

Steel modules, which essentially create a sloping end sill, apparently are assisting in flushing the stilling basin at Old River. Replacing part of the elliptical steps in the stilling basin at Bull Shoals with a smooth ramp created additional hydraulic problems. The debris trap at Pomona is credited with a reduction in erosion, however, circulation of debris is apparently still occurring at some discharge rate. The influence of sloped end sill at Pomona is not known. Leaving the downstream portion of the stilling basin floor at Kinzua at a lower elevation does not appear to have had any effect in reducing erosion.

It is recommended that the effects of any proposed revisions in configuration on the overall performance of a structure be determined through model testing prior to implementation.

Operations

In most cases the presence of debris and subsequent erosion damage to stilling basins were the result of one or more of the following: construction diversion flow through constricted portions of the stilling basin, eddy currents created by diversion flows adjacent to the basin, construction activities above the basin, and nonsymmetrical discharges

into the basin. Until such adverse hydraulic conditions are improved or eliminated, it will be extremely difficult for any of the materials currently being used in construction and repair to perform in the desired manner.

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McDonald, James E

Repair of concrete surfaces subjected to abrasion erosion damage / by James E. McDonald, Tony C. Liu. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. ; available from National Technical Information Service, 1979.

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